

Robust Communication Design in RIS-Assisted THz Channels

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ABSTRACT Terahertz (THz) communication offers the necessary bandwidth to meet the high data rate demands of next-generation wireless systems. However, it faces significant challenges, including severe path loss, dynamic blockages, and beam misalignment, which jeopardize communication reliability. Given that many 6G use cases require both high data rates and strong reliability, robust transmission schemes that achieve high throughput under these challenging conditions are essential for the effective use of high-frequency bands. In this context, we propose a novel mixed-criticality superposition coding scheme for reconfigurable intelligent surface (RIS)-assisted THz systems. This scheme leverages both the strong but intermittent direct line-of-sight link and the more reliable, yet weaker, RIS path to ensure robust delivery of high-criticality data while maintaining high overall throughput. We model a mixed-criticality queuing system and optimize transmit power to meet reliability and queue stability constraints. Simulation results show that our approach significantly reduces queuing delays for critical data while sustaining high overall throughput, outperforming conventional time-sharing methods. Additionally, we examine the impact of blockage, beam misalignment, and beamwidth adaptation on system performance. These results demonstrate that our scheme effectively balances reliability and throughput under challenging conditions, while also underscoring the need for robust beamforming techniques to mitigate the impact of misalignment in RIS-assisted channels.

INDEX TERMS THz communication, reconfigurable intelligent surface, dynamic blockage, beam misalignment, path loss, data significance, criticality, delay, rate, reliability.

I. INTRODUCTION

DRIVEN by the ultra-high data rate demands of future 6G applications, migrating to higher frequency bands, particularly the Terahertz (THz) regime, has emerged as a promising solution. THz communication offers the extensive bandwidth needed to support data-intensive applications, such as extended reality (XR) and digital twins. However, it also faces significant challenges, including severe path loss, molecular absorption, and high penetration and reflection losses. To ensure sufficient signal strength in THz channels, narrow pencil beams are required to focus the transmit power directly at the receiver. However, these highly directional beams make THz channels vulnerable to blockages from

moving obstacles, or even the user itself. Given the severe attenuation of reflected paths in THz bands [2], blockages of the line-of-sight (LoS) path can cause significant disruptions. In addition, pencil-shaped beams are prone to misalignment, even due to micro-mobility of the user. These challenges are exacerbated in dynamic environments, where accurate channel estimation and blockage prediction become nearly impossible. Thus, the unique characteristics of THz communication create a highly unpredictable and dynamic channel, leading to intermittent connectivity [3], [4].

Yet, many 6G applications, such as XR, require not only high data rates, but also strong reliability and low latency to ensure a seamless user experience, particularly for mission-

and safety-critical use cases like healthcare and industrial automation. Consequently, the tradeoff between rate and reliability becomes a fundamental challenge for the effective utilization of high-frequency bands.

In order to mitigate blockages despite the lack of strong multipath components, reconfigurable intelligent surfaces (RIS) are regarded as a promising approach [5], [6], [7], [8]. RIS-assisted channels provide an alternative transmission path that can be less affected by blockages through strategic RIS placement. By dynamically adjusting the phase shifts of the reflective elements, RIS can steer beams toward the receiver, achieving higher signal gain. However, integrating RIS introduces additional complexities, particularly regarding precise beam alignment. The use of narrow beams formed by a large number of reflective elements necessitates substantial overhead for channel estimation, frequent phase reconfiguration, and synchronization between the base station and the RIS controller [9]. Hardware limitations such as discrete phase shifts and imperfections [9], as well as beam squint effects [10], [11] further complicate the implementation and effectiveness of RIS beam steering. Consequently, the practical deployment of highly directive beams in RIS-assisted THz communication poses difficulties, making less directional beams a more practical option. Furthermore, wider beams can address potential misalignments as they enhance robustness against user movements and require less frequent reconfiguration, thereby helping to reduce overhead [12], [13]. However, this advantage comes at the cost of lower gain, making it essential to consider the combined effects of misalignment, beamwidth, and gain reduction when evaluating the effectiveness of RIS deployment. As a result, while the RIS-assisted reflective path is often more reliable than the direct LoS path, it remains significantly weaker. Therefore, this work addresses the challenge of effectively leveraging RIS for blockage mitigation in THz communication by accounting for these trade-offs between reliability and signal strength.

While such a tradeoff is typically addressed by the attempt of finding a compromise between the different objectives, e.g., data rate and outage probability, the paradigm shift in 6G towards goal-oriented communication schemes offers a new perspective. By taking account of the semantic meaning of the transmit data in the context of a specific task or goal, many applications typically comprise heterogeneous data that vary in criticality and significance. For instance, virtual reality (VR) applications place extremely high demands on rate, reliability, and latency, yet the transmitted data can be categorized by varying levels of importance (see Fig. 1). Highly critical data includes real-time positional tracking and interactive feedback, which is essential for an immediate and responsive user experience. Meanwhile, less time-sensitive data, like non-real-time rendering of static components, can tolerate slight delays without significantly affecting the overall VR experience. Similarly, mixed-criticality characteristics also appear in vehicular communications (e.g., safety-critical alerts vs. infotainment services) or smart manufacturing

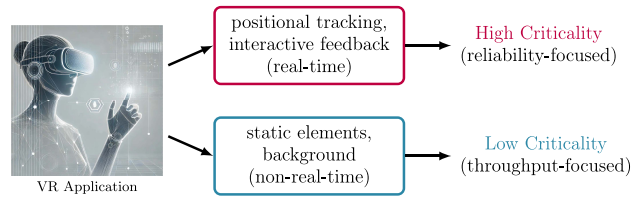


FIGURE 1. Example for data significance classification in a VR application, highlighting different QoS priorities for high- and low-criticality information.

(e.g., real-time machine control commands vs. monitoring data). This motivates a novel approach to handling quality of service (QoS) tradeoffs, namely leveraging service differentiation and prioritization techniques. Criticality-aware transmission schemes can guarantee strictly reliable delivery for particularly critical data segments, while still serving the overall throughput required by an application. This work explores the potential of such a differentiated approach for RIS-assisted THz communication, where data streams of high and low criticality arrive simultaneously and are processed in parallel using superposition coding (SC) to optimize both reliability and throughput.

A. PRIOR ART

THz communication systems face significant challenges due to severe path loss, susceptibility to blockage, and beam misalignment. The deployment of RIS has gained increasing attention as a potential solution to enhance coverage and mitigate blockages in LoS paths, as explored in [5], [14], [15]. RIS are especially promising in high-frequency bands, where channel intermittency and weak multipath components are prevalent, driving research into RIS design for mmWave and THz bands [16], [17]. The potential of RIS-assisted THz communication has been investigated in numerous studies [6], [7], [8], [18], [19], [20]. For instance, in [6], RIS are deployed as THz base stations to enable a seamless user experience in virtual reality applications. In [7], RIS is applied in THz systems to serve users with diverse QoS needs, accounting for coexisting direct and reflective links. While blockage or misalignment effects are overlooked in [7], the impact of dynamic and self-blockage on achieving QoS demands in RIS-aided mmWave and THz networks is analyzed in [18]. The work in [8] examines the coverage probability of RIS-aided THz networks, considering that users can be served via the direct link, the RIS link, or both simultaneously. Despite the strong potential of RIS to enhance coverage, their effective deployment in THz systems presents several key challenges, which remain unaddressed in [7], [8], [18]. These include difficulties in channel state information (CSI) acquisition, beamforming optimization, and mitigating hardware impairments, which can significantly degrade the signal strength achievable through the RIS path [9]. In addition, highly directive beams in THz bands further compromise link reliability due to beam pointing errors and wideband beam split effects, as shown

in [10], [11], [21], [22]. While a few studies have jointly considered the effects of random blockage and misalignment in THz systems [23], [24], [25], their scope is limited to non-RIS-assisted scenarios. Conversely, works that study the impact of misalignment on RIS-assisted THz channels, e.g., [19], [20], do not address random blockages or the combined use of multiple transmission paths with varying gain and reliability characteristics. Thus, to fully exploit the potential of RIS in THz communication, it is essential to jointly address dynamic blockage, beam misalignment and path loss, all of which have a major impact on achievable rates and reliability. In summary, while the direct LoS path suffers from significant intermittency, RIS can provide a more stable alternative link, though typically with lower signal gain, limiting its ability to meet high data rate demands. Consequently, jointly leveraging the strong but intermittent direct link and the more reliable but weaker RIS path is essential to fulfill the QoS requirements of future 6G applications [1]. Many existing studies assume that RIS is only used as a fallback mechanism when the LoS link is unavailable, e.g., [13], [19], [20]. However, given the highly fluctuating nature of THz channels, where blockages occur unpredictably, such reactive approaches fail to ensure consistent connectivity. This underscores the need for proactive strategies that leverage both the direct LoS path and RIS-assisted links simultaneously to mitigate the challenges posed by dynamic environments.

Balancing rate and reliability despite the intermittency and path loss in THz channels, has been explored in several works, e.g., [6], [26], [27], [28]. However, the tradeoff between rate and reliability in THz communication remains largely unexplored from the perspective of data significance or criticality, which is essential for many 6G applications.

The need for developing criticality-aware communication schemes has been addressed in prior works, e.g., [29] or [30], where the consideration of mixed-critical QoS levels has been shown to enhance resilience in resource management. The use of SC to jointly transmit data with varying levels of criticality has been introduced in [31], where multi-connectivity is leveraged in uplink rate-splitting for ultra-reliable low-latency communication, as well as for blockage resilience [32]. Utilizing SC in THz communication has been studied in [33], considering the transmission of multiple streams in a point-to-point link, as well as in multi-user non-orthogonal multiple access (NOMA) scenarios, yet not for the purpose of mixed criticality transmissions. The application of SC for multi-resolution broadcasting has been proposed in [34], where two data streams of different priority are transmitted to two users in a multicast NOMA setting. Different from [34], our work leverages SC to deliver mixed-criticality data to a single user. While this concept is related to hierarchical modulation schemes used in image/video coding, e.g., as in [35], our approach leverages SC for mixed-criticality data delivery in THz systems, aiming to fulfill stringent rate and reliability demands for critical 6G applications.

B. CONTRIBUTION

This work aims to explore the potential of utilizing RIS in THz communication from a data significance perspective. We introduce a novel approach to address the trade-off between rate and reliability requirements, while accounting for the unique challenges of THz systems, including severe path loss, dynamic blockage, and beam misalignment. Specifically, we propose a framework that leverages weak multipath components, particularly a RIS-assisted reflective path, to mitigate the intermittency inherent in THz channels. Assuming that transmit data has different levels of criticality, we address the problem by providing enhanced reliability for high-criticality data using the RIS-path, while less critical data is delivered only when the direct LoS path is available, thereby increasing overall throughput. This novel criticality-aware perspective not only enhances the robustness of RIS-assisted THz systems but also offers new insights into balancing throughput, latency, and reliability in highly dynamic environments. The key contributions can be summarized as follows:

- We study RIS-assisted THz communication under the joint impact of dynamic blockage and beam misalignment. Specifically, we examine downlink transmission through an intermittent LoS link and a more reliable but weaker RIS path (see Fig. 2).
- A novel approach to the rate-reliability tradeoff based on data significance is introduced. We assume that arriving data packets can be classified into high-criticality (HC) and low-criticality (LC) categories. Adopting a cross-layer perspective, the arrival of mixed-criticality data streams is modeled by a queuing system with two separate buffers.
- We propose a mixed-criticality superposition coding (MC-SC) scheme, where both data streams are jointly transmitted via the RIS-assisted channel and successively decoded at the user. The proposed scheme ensures that HC data is reliably delivered as long as either the direct link or the RIS-path is available. In contrast, LC data is only decoded when the LoS path is unblocked. This approach meets reliability constraints for critical transmissions through leveraging path diversity while also maintaining high data rates by utilizing the stronger direct link.
- We formulate a transmit power optimization problem in order to achieve mean queue stability for both data streams, while posing more stringent reliability constraints on the HC data. The non-convex optimization problem is solved iteratively, by applying successive convex approximation and fractional programming techniques.
- Simulations are conducted to evaluate throughput and outage probability for varying ratios of HC and LC data. We analyze this performance tradeoff under varying blockage probabilities and beam pointing errors. Specifically, our findings demonstrate that our proposed

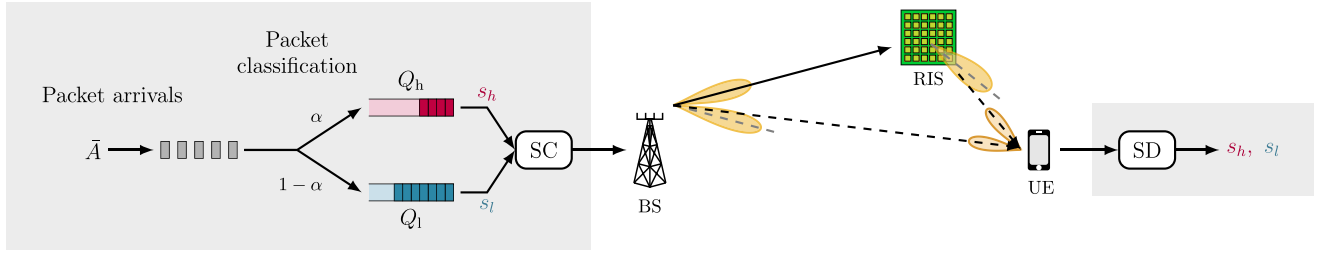


FIGURE 2. System model of a RIS-assisted BS-UE downlink channel. The direct BS-UE link as well as the RIS-UE channel are affected by dynamic blockage and beam misalignment. The arriving packets at the BS are classified according to their criticality and stored in a high- and a low-criticality (HC/LC) buffer. The BS applies superposition coding (SC) of the mixed-criticality data streams and the UE adopts a successive decoding (SD) approach.

scheme, when integrated with beamwidth adaptation strategies, can ensure compliance with HC reliability requirements while achieving significantly higher overall throughput compared to baseline approaches.

- Simulations of the queuing system demonstrate that the proposed scheme achieves significantly lower queuing delay and peak queue length for a substantial portion of HC data, while still meeting the required throughput. Furthermore, the SC scheme is shown to support higher portions of reliable HC transmission compared to a time-sharing approach.

The rest of this paper is organized as follows. Section II presents the system model of the RIS-aided THz channel and introduces the proposed MC-SC scheme. In Section III, the power allocation optimization problem is formulated. Section IV discusses the simulation results, followed by a conclusion in Section V.

Notation: Vectors are denoted by boldface letters. The operators $\mathbb{E}[\cdot]$, $|\cdot|$, and $\text{erf}(\cdot)$ represent the expectation, the absolute value and the error function, respectively. Additionally, $[x]^+$ denotes the positive part of x , i.e., $\max(0, x)$.

II. SYSTEM MODEL

We consider a THz downlink transmission scenario, where a single base station (BS) transmits mixed-criticality data to a single user equipment (UE) via a direct LoS link and a RIS-enabled reflected path as illustrated in Figure 2. Both the BS and the UE are equipped with highly directive antennas, generating narrow beams. At the BS, the data packets intended for the user are classified and assigned to one of two distinct criticality levels, denoted as high-criticality (HC) and low-criticality (LC). These may correspond to different applications or services, which have heterogeneous reliability and latency requirements. Alternatively, within a goal-oriented communication framework, data packets from a single service can be categorized based on their significance (such as in a VR application as illustrated in Fig. 1). Here, we define $\alpha \in [0, 1]$ as the fraction of data classified as HC.

A. CHANNEL MODEL

Due to the severe attenuation induced by scattering in the THz band, we neglect the non-line-of-sight (NLoS) components and only consider the dominant LoS path

(indicated as ‘direct path’) and one RIS-aided reflection path (denoted as ‘RIS-path’) in our channel model. The channel coefficient of the direct link between BS and UE is given by

$$h = \beta_d \eta_d \sqrt{\rho_d}, \quad (1)$$

where $\beta_d \in \{0, 1\}$ is the random blockage variable, η_d denotes the path gain coefficient, and ρ_d captures the misalignment fading. Similarly, the channel coefficient of the RIS-path is defined as

$$g = \beta_r \eta_r \sqrt{\rho_r}. \quad (2)$$

The specific models for blockage, path loss, and misalignment are described next.

1) BLOCKAGE

Due to the high penetration loss THz channels are vulnerable to dynamic blockage caused by other objects or the user itself. Therefore, THz channels suffer from a significant random intermittency that can lead to frequent outages. We assume that with an appropriate RIS placement, the BS-RIS link remains unaffected by such intermittency. Furthermore, since the RIS is positioned closer to the user than the BS, the RIS-assisted path is expected to be more reliable. We model the intermittency of the direct LoS path and the RIS-path using Bernoulli random variables, β_d and β_r , respectively. Each variable equals one when its respective link is available, and zero when the link is blocked. We define blockage probabilities $q_d = \text{Prob}(\beta_d = 0)$ and $q_r = \text{Prob}(\beta_r = 0)$, with $q_r < q_d$.

2) PATH GAIN COEFFICIENT

The channel gain of the direct link is comprising free space path loss and molecular absorption. It is given as [8]

$$\eta_d = \frac{\sqrt{G_B G_U} c}{4\pi f d_{BU}} e^{-\frac{1}{2} k_a(f) d_{BU}}, \quad (3)$$

where G_B and G_U are the antenna gains of the BS and UE, f is the operating frequency, and c is the speed of light. The distance between the BS and the UE is denoted by d_{BU} . The frequency-dependent molecular absorption coefficient is given by $k_a(f)$, which is obtained based on the model presented in [36], valid for the frequency range of 100 – 450 GHz.

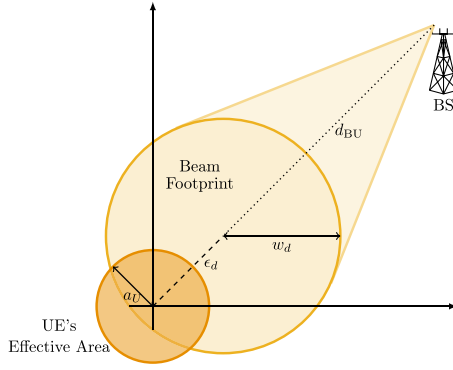


FIGURE 3. Illustration of beam misalignment on the direct BS-UE path, showing the transmission beam footprint and UE's effective area with a pointing error ϵ_d .

Similarly, the channel gain of the RIS path is modeled as

$$\eta_r = \frac{\sqrt{G_B G_R G_U} c}{4\pi f d_{BR} d_{RU}} e^{-\frac{1}{2} k_a(f)(d_{BR} + d_{RU})}. \quad (4)$$

Here, G_R denotes the gain of the RIS-reflected beam, while d_{BR} and d_{RU} are the distances between BS and RIS, and between RIS and UE, respectively.

3) MISALIGNMENT FADING

In addition, pencil-shaped beams entail a high risk for beam misalignment even due to micro-mobility of the user. We use a stochastic model to capture pointing errors as proposed in [37] and widely used for highly directive THz beams [20], [21], [22], [38], [39], [40]. Fig. 3 illustrates the beam misalignment on the direct BS-UE path. The BS is assumed to transmit a highly directive circular beam, which has a Gaussian shape with radius w_d at the distance of the user. The relation between antenna gain G and beamwidth w at distance d for a Gaussian-shaped beam is given by [41]

$$G = \frac{8d^2}{w^2}. \quad (5)$$

From this, we derive the beamwidth at the user as $w_d = \sqrt{8d_{BU}}/\sqrt{G_B}$. The UE has a circular detection beam of radius a_U . The pointing error displacement at the receiver, i.e., the radial distance between the centers of transmission and reception beams, is denoted by ϵ_d . The received power is calculated by integrating the BS beam power across the UE's effective area. From [37], the misalignment fading coefficient ρ_d , representing the power fraction collected via the direct LoS link, is approximated as follows:

$$\rho_d \approx A_d \exp\left(-\frac{2\epsilon_d^2}{w_{eq,d}^2}\right). \quad (6)$$

This equation captures the exponential decay of received power as misalignment ϵ_d increases. Here, A_d represents the maximum collected power fraction via the direct path under perfect beam alignment, i.e., $\epsilon_d = 0$. Assuming Gaussian beams, it is given as

$$A_d = \text{erf}(v_d)^2, \quad (7)$$

where

$$v_d = \frac{\sqrt{\pi} a_U}{\sqrt{2} w_d}. \quad (8)$$

In (8), a_U is the radius of the effective area of the reception antenna, which, according to [40], is given by

$$a_U = \frac{c\sqrt{G_U}}{2\pi f}. \quad (9)$$

In (6), $w_{eq,d}$ denotes the equivalent beamwidth as defined in [37], and is obtained from w_d via the following relation:

$$w_{eq,d}^2 = w_d^2 \frac{\sqrt{\pi} \text{erf}(v_d)}{2v_d \exp(-v_d^2)}. \quad (10)$$

We assume that ϵ_d follows a Rayleigh distribution with variance $\sigma_{m,d}^2$, as in [37], [40]. Then, the probability density function (PDF) of ρ_d can be written as

$$f_{\rho_d}(x) = \frac{\gamma_d^2}{A_d^{\gamma_d^2}} x^{\gamma_d^2 - 1}, \quad 0 \leq x \leq A_d, \quad (11)$$

in which

$$\gamma_d = \frac{w_{eq,d}}{2\sigma_{m,d}}. \quad (12)$$

Hence, the cumulative distribution function (CDF) follows from (11) as

$$F_{\rho_d}(x) = \left(\frac{x}{A_d}\right)^{\gamma_d^2}, \quad 0 \leq x \leq A_d. \quad (13)$$

For the RIS-path, we have $\rho_r = \rho_{r1}\rho_{r2}$, where ρ_{r1} and ρ_{r2} are the fraction of collected power via the BS-RIS path and the RIS-UE path, respectively. We assume that the transmit beam of the BS to the RIS is perfectly aligned, given the static placement of BS antenna and RIS. With no misalignment on this link, this leads to $\rho_{r1} = A_{RIS}$, where A_{RIS} represents the fraction of power collected by the RIS from the BS beam and is obtained similarly to (7) – (8). Here, the width of the BS beam on the RIS surface is obtained from the relation (5) and the radius of the RIS effective area is approximated based on its physical dimensions [42] as $a_{RIS} = \frac{\lambda}{4} \sqrt{N_R}$, assuming a RIS with $\sqrt{N_R} \times \sqrt{N_R}$ elements of size $\lambda/2$. In turn, the reflective beam of the RIS is subject to random pointing errors, modeled by the displacement ϵ_r . The reflected beam is assumed to have a circular shape with radius w_r at the UE. Thus, based on the previously described misalignment fading model [37], the fraction of collected power via the RIS-path is expressed as

$$\rho_r \approx A_{RIS} A_r \exp\left(-\frac{2\epsilon_r^2}{w_{eq,r}^2}\right). \quad (14)$$

In (14), A_r is the maximum power fraction collected via the RIS-UE link with perfect alignment, and $w_{eq,r}$ denotes the equivalent width of the reflected beam. These parameters for the RIS-UE path are derived analogously to the direct path, following equations (7) – (10).

For tractability, we assume that the pointing errors of the two propagation paths are independent. This assumption is reasonable under strategic RIS placement, where the angles of arrival from the RIS and the BS are sufficiently distinct. Additionally, beam pointing errors can arise not only from user micro-mobility but also due to factors such as coarse codebooks, hardware constraints, or delayed beam adjustment. These factors can affect each path differently, further reducing any correlation. Consequently, we model ϵ_r as independent of ϵ_d , with ϵ_r following a Rayleigh distribution with variance $\sigma_{m,r}^2$. Hence, the distribution of ρ_r is analogous to (11) and (13), with parameter $\gamma_r = \frac{w_{eq,r}}{2\sigma_{m,r}}$. As previously discussed, beam training and phase configuration at the RIS are particularly challenging [9]. Due to less frequent beam adjustments, the RIS beam may experience greater misalignment variance than the direct beam. Therefore, in our model we assume $\sigma_{m,r} > \sigma_{m,d}$. Furthermore, we assume that the reflected beam is wider than the direct beam due to a coarser codebook design and potential hardware limitations.

Channel uncertainty at the BS arises from the blockage state, represented by $\beta = [\beta_d, \beta_r]$, and the pointing error displacement, given by $\epsilon = [\epsilon_d, \epsilon_r]$, which affect both the direct path and the RIS link. We assume that the BS has only statistical knowledge of β and ϵ , characterized by the blockage probabilities q_d and q_r , as well as the misalignment variances $\sigma_{m,d}^2$ and $\sigma_{m,r}^2$. Our goal is to ensure robust transmission despite these uncertainties, which are particularly detrimental in (sub-)THz bands.

B. MIXED CRITICALITY SUPERPOSITION CODING

In our proposed scheme, SC is applied to the mixed-criticality data, allowing simultaneous transmission over the same frequency resources, while the user applies a successive decoding strategy. Here, higher transmit power is allocated to the HC data, enabling it to be decoded even under weaker channel conditions. In contrast, the LC data is successively decoded only when the channel is sufficiently strong. When applied to a RIS-aided THz channel with LoS intermittency, our scheme allows the decoding of the critical stream even if either one of the links is blocked, whereas the non-critical data remains decodable only when the LoS is available. This strategy is illustrated in Fig. 4. Furthermore, with more power allocated to the HC stream and by leveraging path diversity, critical data experiences fewer outages caused by beam misalignment.

Remark 1: Our MC-SC scheme is conceptually related to power-domain NOMA (e.g., [43]), which serves multiple users by superimposing signals at different power levels, enabling both a near (strong) and a far (weak) user to share the same channel. In our single-user design, the user similarly adapts to channel conditions: when the direct LoS path is available, both messages are decoded, but when the LoS is blocked, the UE acts as a ‘weak user’, decoding only the critical message. This approach enhances the robustness

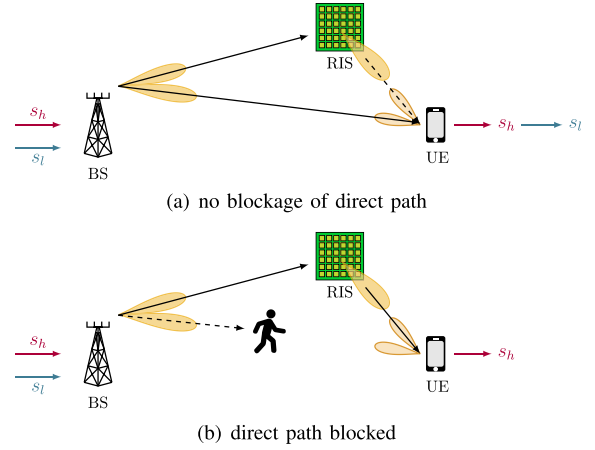


FIGURE 4. Illustration of mixed-criticality transmission scheme: (a) As long as the direct path is available, both messages are successively decoded at the UE. (b) If the direct path is blocked, only the HC message is decoded via the RIS-path.

of critical message transmission against unexpected and unpredictable deep fades.

In the proposed scheme, the HC and LC messages, denoted by s_h and s_l , respectively, are encoded and transmitted using two separate beams directed at the UE and the RIS. We assume that the Angles of Departure (AoD) for the UE and RIS directions differ significantly compared to the narrow beamwidths and side lobes are negligible. This spatial separation allows for perfect isolation of the direct path and the RIS path. Accordingly, we define separate transmit signals for the beams directed at the UE and RIS as x_d and x_r , respectively. By applying SC to the HC and LC messages, the transmit signals are given by:

$$x_d = \sqrt{p_h^{(d)}} s_h + \sqrt{p_l^{(d)}} s_l, \quad (15)$$

$$x_r = \sqrt{p_h^{(r)}} s_h + \sqrt{p_l^{(r)}} s_l, \quad (16)$$

where $p_h^{(d)}$ ($p_l^{(d)}$) and $p_h^{(r)}$ ($p_l^{(r)}$) are the transmit power allocated to the HC (LC) message in the direction of the user and the RIS, respectively. The received signal at the UE is then expressed as

$$y = hx_d + gx_r + n, \quad (17)$$

in which $n \in \mathcal{CN}(0, \sigma_n^2)$ is additive white Gaussian noise (AWGN).

The user successively decodes both messages, starting with the HC message. Thus, the signal-to-interference-plus-noise ratio (SINR) of the HC message can be written as

$$\Gamma_h(\beta, \epsilon) = \frac{|h|^2 p_h^{(d)} + |g|^2 p_h^{(r)}}{|h|^2 p_l^{(d)} + |g|^2 p_l^{(r)} + \sigma_n^2}, \quad (18)$$

where the channel gains $|h|^2$ and $|g|^2$ of the direct and reflective path are determined based on (1) with the blockage and misalignment states given by β and ϵ . After correctly decoding and subtracting the HC message from the received

signal, the LC data can be decoded, whereby the signal-to-noise-ratio (SNR) is given by

$$\Gamma_l(\boldsymbol{\beta}, \boldsymbol{\epsilon}) = \frac{|h|^2 p_l^{(d)} + |g|^2 p_l^{(r)}}{\sigma_n^2}. \quad (19)$$

As a result, the achievable data rates with bandwidth B are obtained as

$$r_h = B \log_2(1 + \Gamma_h(\boldsymbol{\beta}, \boldsymbol{\epsilon})), \quad (20)$$

$$r_l = B \log_2(1 + \Gamma_l(\boldsymbol{\beta}, \boldsymbol{\epsilon})). \quad (21)$$

Let R_h and R_l denote HC and LC target rates and ξ_h and ξ_l be binary variables that are equal to one to indicate successful decoding of the HC and LC message, respectively, and equal to zero in case of an outage. Then, we have

$$\xi_h = \begin{cases} 1, & \text{if } r_h \geq R_h, \\ 0, & \text{if } r_h < R_h. \end{cases} \quad (22)$$

As the decoding of the LC message depends on successful interference cancellation of the HC message, we have

$$\xi_l = \begin{cases} 1, & \text{if } \xi_h = 1 \text{ and } r_l \geq R_l, \\ 0, & \text{otherwise.} \end{cases} \quad (23)$$

C. QUEUING MODEL

As shown in Fig. 2, we adopt a queuing model at the BS, where packet arrivals are assumed to follow a Poisson process with arrival rate \bar{A} . The arriving packets are then classified according to their criticality level, whereby a fraction of α data packets is considered HC data. We model the evolution of the two data queues containing HC and LC packets as follows:

$$Q_h(t) = \left[Q_h(t-1) - \xi_h \frac{T}{M} R_h(t) \right]^+ + \alpha A(t), \quad (24)$$

$$Q_l(t) = \left[Q_l(t-1) - \xi_l \frac{T}{M} R_l(t) \right]^+ + (1 - \alpha) A(t). \quad (25)$$

Here, $Q_h(t)$ and $Q_l(t)$ are the number of buffered HC and LC packets, and $A(t)$ represents the total packet arrivals in time slot t , respectively. The packet size is denoted by M , and T is the time slot duration. To avoid buffer overflow, the transmission scheme must ensure that all queues remain stable. A queue is considered stable if

$$\lim_{t \rightarrow \infty} \sup \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}[Q(\tau)] < \infty. \quad (26)$$

In the long term, mean rate stability is achieved when the average departure rate exceeds the average arrival rate [44].

According to Little's law [45], the average queuing delay, i.e., the mean waiting time of HC and LC data in each buffer, is given as

$$\tau_h = \frac{\mathbb{E}\{Q_h\}}{\alpha \bar{A}} \quad \text{and} \quad \tau_l = \frac{\mathbb{E}\{Q_l\}}{(1 - \alpha) \bar{A}}. \quad (27)$$

Next, we formulate a power allocation problem to ensure mean queue stability while applying more stringent reliability constraints to the HC data.

III. PROBLEM FORMULATION

Our goal is to serve the throughput demand specified by the packet arrival rate \bar{A} , while ensuring high reliability for the data classified as HC despite the fluctuating THz channel. More precisely, with the proposed SC scheme defined in (15) and (16), we require the HC data to be decodable via the RIS if the direct link is blocked and vice versa. Hence, while the LC data stream suffers from outages whenever the direct LoS path is blocked, the HC data stream is disrupted only when both the LoS and the RIS-link become unavailable (see Fig. 4). Additionally, we aim to stabilize connectivity in the presence of beam misalignment errors. Creating path diversity by leveraging RIS partly mitigates outages caused by spatial jitter and inaccurate beam configurations. To ensure robustness against small pointing errors, we adopt a heuristic approach, where decoding is successful via the direct link (RIS-link) as long as $\rho_d \geq \frac{1}{2} A_d$ ($\rho_r \geq \frac{1}{2} A_{\text{RIS}A_r}$). Thereby, a link is assumed to become unavailable for beam displacements that lead to a power reduction exceeding 50% at the receiver. This aligns with other works assuming that outages occur when beam misalignment exceeds the half-power beamwidth, e.g., [46]. Thus, we formulate rate constraints based on the half-power beam gain, which occurs at the pointing error threshold $\epsilon_{th} = \sqrt{\ln(\sqrt{2})[w_{\text{eq},d}, w_{\text{eq},r}]}$, derived from (6) with $\rho_d = \frac{1}{2} A_d$. Thereby, the misdetection probability via the direct path caused by misalignment is obtained from (13) as

$$q_{m,d} = F_{\rho_d} \left(\frac{A_d}{2} \right) = \left(\frac{1}{2} \right)^{\gamma_d^2}. \quad (28)$$

Analogously, the misdetection probability due to misalignment on the RIS-path follows as $q_{m,r} = \left(\frac{1}{2} \right)^{\gamma_r^2}$.

The outage probabilities can be derived from the blockage and misalignment probabilities as follows. Since LC data transmission relies solely on the availability of the direct path, it can be decoded only when this path is unblocked and the pointing error ϵ_d remains within the acceptable threshold. Thus, the outage probability for LC data is given by

$$P_{\text{out},l} = \text{Prob}(\xi_l = 0) = 1 - (1 - q_d)(1 - q_{m,d}). \quad (29)$$

For HC data, an outage occurs only if both the direct and RIS path fail to support decoding due to either blockage or misalignment. Note that in case of misalignment, decoding could be successful using the combined signal from both paths, even if individual paths do not provide sufficient signal strength. However, for simplicity, we approximate the outage probability by treating the paths independently, leading to

$$\begin{aligned} P_{\text{out},h} &= \text{Prob}(\xi_h = 0) \\ &\approx (1 - (1 - q_d)(1 - q_{m,d})) \cdot (1 - (1 - q_r)(1 - q_{m,r})). \end{aligned} \quad (30)$$

We formulate an optimization problem to find the optimal power allocation that stabilizes both (HC and LC) queues for the throughput requirements given by the packet arrival

rate \bar{A} and HC packet ratio α . Note that mean queue stability is achieved when the average service rate is greater than the arrival rate [44]. From (24), the mean stability constraint for the HC queue is expressed as

$$\mathbb{E}\left[\xi_h \frac{T}{M} R_h(t)\right] > \alpha \bar{A}. \quad (31)$$

Here, the expected HC throughput is determined as $\mathbb{E}[\xi_h R_h(t)] = (1 - P_{\text{out},h}) R_h$, where R_h is the coding rate. The LC stability constraint is derived analogously. We introduce the optimization variable $\delta = [\delta_h, \delta_l]$ representing the gap between the rate of successfully delivered packets and the packet arrival rate. Queue stability is achieved when δ_h and δ_l are positive. A larger δ enhances robustness against packet arrival bursts and allows packet accumulation to be cleared more quickly, enabling faster recovery from outages. Therefore, as optimization objective, we maximize the minimum of the weighted gap variables δ in order to also ensure fairness for both queues.

Hence, defining $\mathbf{p} = [p_h^{(d)}, p_h^{(r)}, p_l^{(d)}, p_l^{(r)}]$ and $\mathbf{R} = [R_h, R_l]$, our optimization problem is formulated as follows:

$$\max_{\delta, \mathbf{p}, \mathbf{R}} \min\{w_h \delta_h, w_l \delta_l\} \quad (32)$$

$$\text{s.t.} \quad (1 - P_{\text{out},h}) \frac{T}{M} R_h - \alpha \bar{A} \geq \delta_h, \quad (32a)$$

$$(1 - P_{\text{out},l}) \frac{T}{M} R_l - (1 - \alpha) \bar{A} \geq \delta_l, \quad (32b)$$

$$\delta_h, \delta_l \geq 0, \quad (32c)$$

$$R_h \leq B \log_2(1 + \Gamma_h(\boldsymbol{\beta}, \boldsymbol{\epsilon}_{th})), \\ \forall \boldsymbol{\beta} \in \{(0, 1), (1, 0), (1, 1)\}, \quad (32d)$$

$$R_l \leq B \log_2(1 + \Gamma_l(\boldsymbol{\beta}, \boldsymbol{\epsilon}_{th})), \quad \boldsymbol{\beta}_d = 1, \quad (32e)$$

$$p_h^{(d)} + p_h^{(r)} + p_l^{(d)} + p_l^{(r)} \leq P_{\text{max}}. \quad (32f)$$

Here, the constraints (32a), (32b), and (32c) provide mean stability of the HC and LC queue. Meanwhile, (32d) ensures that the HC data stream can be decoded as long as at least one of the two paths are available. The LC data stream, however, is only required to be decodable if the direct link exists as specified in (32e). Finally, (32f) is the transmit power constraint of the BS. The weights w_h and w_l in the objective function allow for queue prioritization. In this work, we select $w_h = \frac{1}{\alpha}$ and $w_l = \frac{1}{1-\alpha}$, ensuring that the optimized gap δ^* is proportional to the queue throughput. Alternative objective functions, such as maximizing the weighted sum of δ variables, could lead to disproportionate prioritization of one queue, leaving the other barely stabilized with δ near zero. This imbalance may cause severe packet accumulation during blockages and prolonged recovery times. The max-min fairness approach adopted in this work prevents such issues by ensuring balanced stabilization for both queues in the long term. Even when the mean stability condition is satisfied for both queues, the expected backlog and average waiting times remain non-zero as they depend not only on δ but also on service variability. As a result, despite

TABLE 1. Simulation parameters (if not stated otherwise).

Transmit power P_{max}	10 dBm
Noise power N_0	-174 dBm/Hz
Antenna gain G_B, G_U	40 dB, 35 dB
Bandwidth B	10 GHz
Distances $d_{\text{BU}}, d_{\text{BR}}, d_{\text{RU}}$	15 m, 15.8 m, 5 m
Carrier frequency f	300 GHz
Mol. absorption coeff. $k_a(f)$	0.0012 m ⁻¹
RIS elements N_R	200 × 200
Blockage prob. q_d, q_r	0.3, 0.1
Misalignment standard deviation $\sigma_{m,d}, \sigma_{m,r}$	0.1, 0.2
RIS reflected beamwidth at UE w_r	0.8 m

achieving fairness in steady-state behavior, LC packets generally experience higher delays due to their intermittent service rate, which results in greater backlog accumulation during outages and longer recovery times. In contrast, HC packets benefit from a more stable service rate ensured by constraint (32d), which mitigates delays during blockages. Note that as the transmission of LC data solely relies on the direct LoS path, the optimal power allocation leads to $p_l^{(r)*} = 0$, i.e., the beam transmitted towards the RIS only contains a HC signal component.

The problem (32) is non-convex due to the rate expressions. Thus, we adopt a successive convex approximation (SCA) approach to iteratively optimize the power allocation. Based on a fractional programming framework proposed in [47], the original problem is approximated by a convex problem via a quadratic transform that is applied to the fractional SINR expressions. The detailed problem reformulation and the iterative algorithm are given in the Appendix.

IV. NUMERICAL RESULTS

The performance of our proposed MC-SC scheme is evaluated through numerical simulations with the parameters given in Table 1. We compare our scheme with several traditional benchmark schemes:

- *Traditional LoS communication (without RIS)*: This corresponds to a special case of our proposed scheme, where $\alpha = 0$, i.e., all data is treated as LC.
- *RIS-assisted multi-beam communication*: In this case, both the direct and the RIS path are used simultaneously for a single data stream. This corresponds to the special case, where $\alpha = 1$, i.e., all data is treated as HC.
- *Time-sharing scheme*: We consider a benchmark time-sharing scheme in which each time slot is divided into two phases: a LoS-only phase ($\alpha = 0$) and a RIS-assisted phase ($\alpha = 1$).
- *Beam Switching Scheme*: In this scheme, data is transmitted via the LoS path whenever it is available. In the event of LoS blockage, the RIS-aided reflective path is used instead. Beam switching relies on timely blockage detection, which is impractical for THz communication

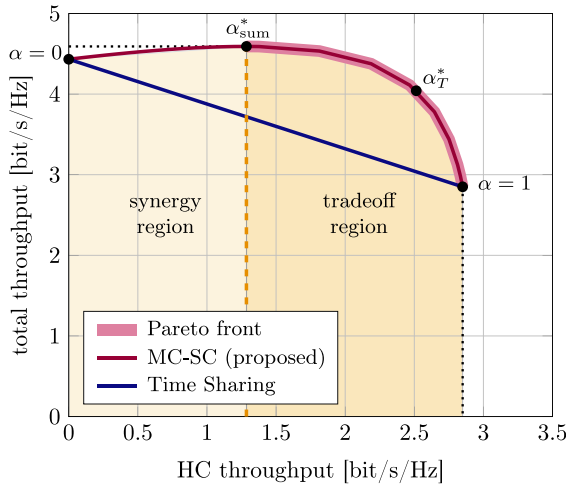


FIGURE 5. Feasibility region of the proposed MC-SC scheme in comparison to time sharing, showing the total achievable throughput versus the achievable HC throughput for $\alpha \in [0, 1]$. The overall throughput is maximized at α_{sum}^* . For $\alpha < \alpha_{\text{sum}}^*$, total throughput and the portion of reliable HC rate have a synergetic relation, whereas a tradeoff is exhibited for $\alpha > \alpha_{\text{sum}}^*$. All points on the thick red line are Pareto optimal, and a tradeoff solution balancing throughput and reliability by solving (33) is achieved with α_T^* .

due to high absorption and frequent dynamic blockages caused by narrow pencil beams. Therefore, this work assumes the blockage state is unknown to the BS. Consequently, the beam switching scheme represents a theoretical upper bound, illustrating the performance gap between scenarios with perfect and unknown blockage state knowledge.

We begin by analyzing the achievable performance in terms of throughput and outage probability under the combined effects of blockage and misalignment, followed by a detailed queuing system analysis.

A. ACHIEVABILITY ANALYSIS

In the following, we explore the tradeoff between achievable throughput and reliability with our proposed scheme. First, we analyze the feasibility region of (32) in Fig. 5. To this end, we evaluate the maximum feasible \bar{A} , denoted by \bar{A}_{max} , representing the achievable throughput, for different values of $\alpha \in [0, 1]$. Note that at the border of the feasibility region, we obtain $\delta_h = \delta_l = 0$. Fig. 5 illustrates the feasible region of total throughput and the corresponding portion of HC throughput achieved with our proposed MC-SC scheme.

For $\alpha = 0$, where all data is treated as LC and transmitted solely via the direct LoS link, a maximum throughput of 4.4 bit/s/Hz is achieved. When $\alpha = 1$, meaning all data is treated as HC, the achievable throughput decreases to 2.8 bit/s/Hz. This reduction occurs because, for the HC data, the transmit power is divided between the direct path and the RIS-link, and the stricter constraint in (32d) ensures successful decoding even when one of the paths is blocked. Consequently, the higher reliability required for HC data comes at the cost of lower transmission rate, which is not fully compensated by the reduced outage probability.

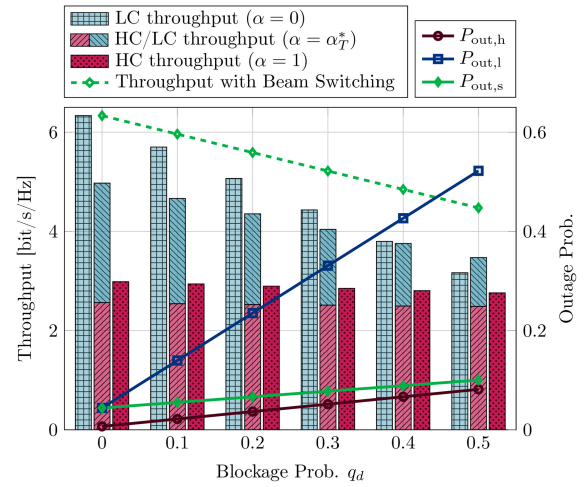


FIGURE 6. Throughput and outage probabilities under varying blockage probabilities of the direct path. Bars represent HC and LC throughput for $\alpha = 0, \alpha_T^*$, and $\alpha = 1$ (left to right). The dashed green line shows throughput with perfect blockage state knowledge and beam switching, while solid lines show the corresponding outage probabilities.

We observe that the achievable rate region with SC is significantly larger compared to a time sharing approach. Additionally, as α increases, the total throughput initially rises, reaching a maximum at $\alpha_{\text{sum}}^* = 0.28$. This synergistic behavior occurs because, although the direct path has higher channel gains, frequent blockages lead to outages that reduce throughput. By using SC and exploiting path diversity for HC data, outages are reduced, resulting in improved throughput even with a lower transmission rate. However, as α continues to increase, the overall throughput decreases due to greater reliance on the weaker RIS channel. This introduces a tradeoff between total throughput and HC rate for $\alpha \in [\alpha_{\text{sum}}^*, 1]$. The Pareto-optimal points are highlighted by the thick red line in Fig. 5. The optimal value of α should be selected within the range $[\alpha_{\text{sum}}^*, 1]$, whereby the desired tradeoff depends on the specific application requirements. For further analysis of our scheme, we suggest an optimal tradeoff solution that maximizes the sum of the normalized total throughput and HC throughput. Specifically, we define

$$\alpha_T^* = \arg \max_{\alpha} \frac{\bar{A}_{\text{max}}(\alpha)}{\bar{A}_{\text{max}}(\alpha_{\text{sum}}^*)} + \frac{\alpha \bar{A}_{\text{max}}(\alpha)}{\bar{A}_{\text{max}}(\alpha = 1)}. \quad (33)$$

The solution to (33) can be determined using one-dimensional search algorithms such as golden section search. In the simulation depicted in Fig. 5, the tradeoff solution is found at $\alpha_T^* = 0.62$. With this choice of α , the HC throughput nearly doubles compared to the maximum throughput solution, while the total throughput is reduced by only 12%.

Next, we analyze the impact of blockage probability and misalignment variance on the optimal tradeoff solution for α . Fig. 6 shows the achievable HC and LC throughput, as well as the corresponding outage probabilities, as functions of the direct path's blockage probability. We evaluate the throughput performance of our proposed MC-SC scheme

with tradeoff parameter α_T^* , and compare it with three benchmarks: (1) direct path only ($\alpha = 0$), (2) treating all data as HC ($\alpha = 1$), and (3) beam switching with perfect blockage state knowledge at the BS. As the blockage probability increases, the outage probabilities for both HC and LC data rise. However, HC transmission is less affected by direct path blockage due to the exploitation of the more reliable RIS path. As a consequence of less reliable transmissions, the throughput declines with increasing q_d . With $\alpha = 0$, the direct path achieves high throughput of 6.3 bit/s/Hz when unblocked. However, when the direct link is available only 50% of the time, throughput drops significantly to 3.2 bit/s/Hz. In contrast, using both transmission paths ($\alpha = 1$) provides greater robustness, with a lower rate that is less affected by the intermittency of the direct path. Therefore, while with $\alpha = 1$, only 3 bit/s/Hz are achievable even when $q_d = 0$, the throughput decreases by just 7.4% when $q_d = 0.5$. With the proposed MC-SC scheme and the tradeoff parameter set to $\alpha = \alpha_T^*$, a significant portion of HC data can be transmitted with higher reliability, while still maintaining high overall throughput. As the direct path becomes increasingly intermittent, total throughput decreases by 30% from 5 to 3.5 bit/s/Hz, but HC throughput remains around 2.5 bit/s/Hz. The beam switching benchmark achieves the highest throughput, yet under the assumption of perfectly known blockage state at the BS, which enables ideal beam switching to the RIS link when the direct link is blocked. Consequently, outages occur only when both links are blocked or due to beam misalignment affecting the active link, leading to the overall outage probability

$$P_{\text{out},s} = q_d(q_r + (1 - q_r)q_{m,r}) + (1 - q_d)q_{m,d}.$$

We observe that the MC-SC scheme achieves similar robustness for HC data *without knowledge of the blockage state* by utilizing both links simultaneously. Notably, the outage probability of HC data in MC-SC is even lower than that of beam switching, as the path diversity inherent to HC transmission partly mitigates misalignment effects, whereas beam switching relies on a single link at a time. However, this robustness in MC-SC comes at the cost of higher resource consumption, resulting in lower throughput. When all data is treated as HC ($\alpha = 1$), the throughput loss compared to the ideal blockage-aware beam-switching case is substantial. However, the proposed MC-SC scheme with α_T^* narrows this gap by half or more, while ensuring the reliable delivery of a significant portion of HC data.

It is important to note that when the direct path is reliable (i.e., $q_d = 0$), the benefit of using the additional RIS-assisted path in terms of outage probability is rather low, while the loss in throughput is significant. However, for high q_d , the RIS-path greatly reduces outages with only a minor drop in throughput. Therefore, the difference between $P_{\text{out},h}$ and $P_{\text{out},l}$ should be considered when selecting α . Thus, in case of a rather reliable direct path, a lower α should be chosen to achieve higher data rates, whereas with an unreliable direct

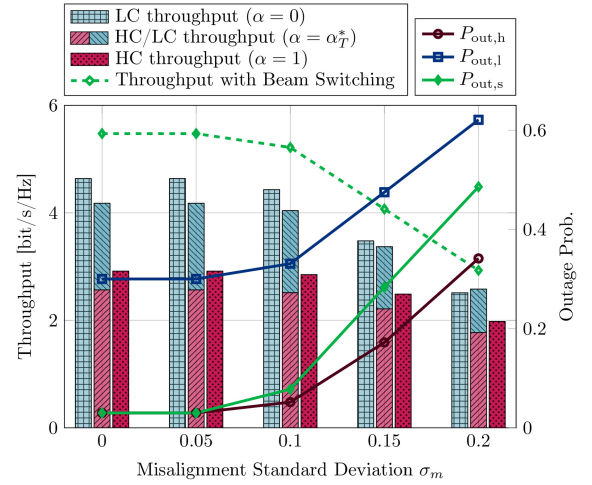


FIGURE 7. Impact of beam misalignment on throughput and outage probabilities. Bars represent HC and LC throughput for $\alpha = 0$, α_T^* , and $\alpha = 1$ (left to right). The dashed green line shows throughput with perfect blockage state knowledge and beam switching, while solid lines show the corresponding outage probabilities.

link, prioritizing reliability over throughput by selecting a larger α is more beneficial.

Fig. 7 shows the achievable throughput and corresponding outage probabilities for varying beam misalignment standard deviations. Here, we set $\sigma_{m,d} = \frac{1}{2}\sigma_{m,r} = \sigma_m$. Again, we compare the performance of the proposed MC-SC scheme with α_T^* against the benchmarks $\alpha = 0$, $\alpha = 1$, and beam switching. As expected, outage probabilities increase significantly with greater misalignment (beyond $\sigma_m = 0.1$), for both HC and LC transmissions and with beam switching. Although $P_{\text{out},h}$ remains much lower than $P_{\text{out},l}$, both exhibit similar growth as misalignment affects both links. With beam switching, $P_{\text{out},s}$ is close to $P_{\text{out},h}$ when the misalignment effect is small, but increases more rapidly with growing σ_m . This again demonstrates the enhanced robustness due to path diversity for HC transmissions compared to switching between beams. The overall decline in reliability due to misalignment is reflected also in the throughput, which decreases as σ_m increases. While beam switching under ideal blockage-awareness conditions continues to achieve the highest throughput, its advantage diminishes significantly as misalignment becomes more pronounced. In the other schemes, LC throughput declines more rapidly than HC throughput due to the higher risk of outages. With the proposed MC-SC scheme and $\alpha = \alpha_T^*$, the achievable HC throughput is just slightly reduced compared to $\alpha = 1$, yet the total throughput is substantially higher and significantly closer to the upper bound given by beam switching. For $\sigma_m = 0.2$, the total throughput achieved with the tradeoff solution even exceeds the LC throughput with $\alpha = 0$. As σ_m increases, the value of α_T^* rises, since the adverse effects of misalignment make the use of the additional RIS path more beneficial, despite the reduced channel gain. However, while a larger portion of data can be treated as HC with higher σ_m , the HC transmission also becomes less reliable, which may

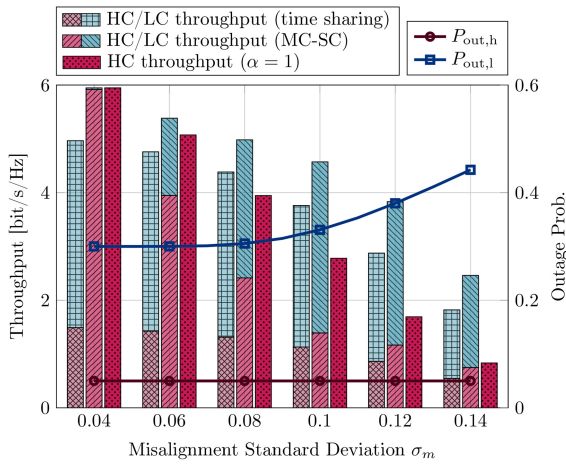


FIGURE 8. Throughput and outage probabilities under varying beam misalignment standard deviation in a scenario with strict HC requirements. Bars represent HC and LC throughput for a time sharing approach with $\alpha = 0.3$, MC-SC with $\alpha \geq 0.3$, and the maximum HC throughput with $\alpha = 1$ (left to right). Lines indicate the corresponding outage probabilities, whereby $P_{\text{out},h} = 0.05$ is guaranteed for all values of σ_m .

be unsuitable for the functionality of certain applications. This highlights the need for robustness measures to mitigate the impact of misalignment.

Therefore, in Fig. 8, we study a scenario with strict HC requirements. In this case, at least 30% of the data must be transmitted as HC (i.e., $\alpha \geq 0.3$), with an outage probability of $P_{\text{out},h} = 0.05$. As beam pointing errors increase, robustness measures are necessary to ensure the required reliability for HC data, e.g., through the employment of effective beamforming strategies. We apply a beamwidth adaptation approach to maintain a constant outage probability for HC transmission despite varying σ_m . Specifically, the beamwidth of the reflected beam w_r is adjusted to meet the desired $P_{\text{out},h}$.¹ This comes at the cost of a reduced gain G_R , as given by (5). Note that widening the reflective beam improves the reliability of the RIS path, but also leads to higher path attenuation, thereby intensifying the disparity between the direct path and the RIS path. Fig. 8 shows the achievable HC and LC throughput, along with their corresponding outage probabilities, under these conditions. We compare three different strategies: (1) time sharing with $\alpha = 0.3$, (2) the proposed MC-SC with $\alpha = \max(0.3, \alpha_{\text{sum}}^*)$, and (3) treating all data as HC ($\alpha = 1$). All three transmission strategies involve beamwidth adjustment by the RIS and meet the given HC requirements.

When beam pointing errors are small, the RIS can create a highly directive beam toward the UE without violating the required HC reliability constraints.² This narrow beam results in higher gain, strengthening the RIS path. Consequently, at $\sigma_m = 0.04$, the highest throughput is achieved when $\alpha = 1$. However, as misalignment increases,

¹Approaches for RIS beam design with tunable beamwidth have been proposed in [12], [13].

²Note that the beam focusing capability of the RIS is restricted by several factors, such as the number of reflective elements and the discrete phase shifter resolution, which are not considered in this simulation.

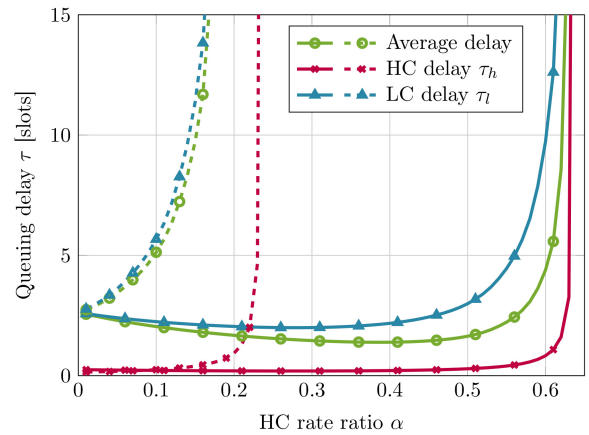


FIGURE 9. Average packet waiting time in the queue as a function of the HC rate ratio α for our proposed MC-SC scheme (solid lines) and a time sharing scheme as baseline (dashed lines).

the reflective beam must be widened to maintain the required $P_{\text{out},h}$, leading to a rapid decrease of HC throughput. Thus, imposing strict HC requirements on all data (i.e., $\alpha = 1$) leads to a significant decline in overall throughput. Applying the data significance approach with time sharing, where only 30% of the data must meet strict reliability standards, the total throughput decreases more slowly. However, the proposed MC-SC scheme outperforms both other strategies in terms of total throughput across the entire range of σ_m . Note that for $\sigma_m < 0.1$, we have $\alpha_{\text{sum}}^* > 0.3$, meaning that more than the required 30% of data is transmitted as HC. For $\sigma_m \geq 0.1$, $\alpha = 0.3$ is chosen to meet the requirements, though this is not throughput-optimal. Nevertheless, with high impact of misalignment at $\sigma_m = 0.14$, the MC-SC scheme nearly triples the total throughput compared to the scenario where all data is treated as HC ($\alpha = 1$). Additionally, MC-SC provides a 35% improvement in throughput over the time sharing approach.

In summary, the results from Figs. 7 and 8 demonstrate that while RIS is promising for mitigating dynamic blockages in THz communications, beam pointing errors must be accounted for. Applications with strict reliability requirements necessitate robust transmission strategies, such as beamwidth adaptation [28], to address spatial jitter and user micro-mobility. However, these techniques come at the cost of reduced beamforming gain, intensifying the tradeoff between rate and reliability. Therefore, transmission schemes that consider data significance, like the proposed MC-SC, are a promising solution to balance these conflicting application requirements.

B. QUEUING SYSTEM ANALYSIS

Next, we evaluate the average queuing delay, i.e., the mean waiting time of HC/LC data in each buffer, as obtained from (27). Fig. 9 shows the average queuing delay for a packet size of $M = 5$ Mbit, time slot duration $T = 100$ ms, and a total packet arrival rate of $\bar{A} = 800$ packets/slot. We compare the proposed MC-SC scheme with a time sharing

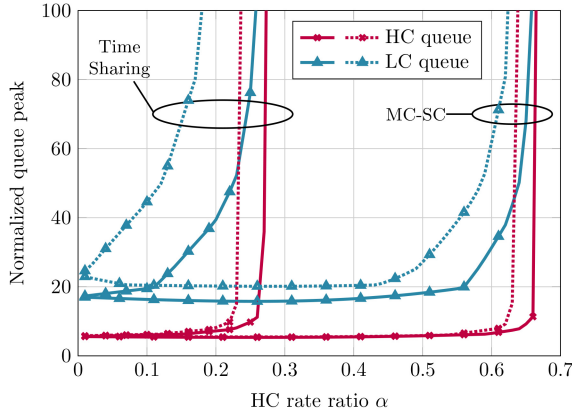


FIGURE 10. Normalized peak queue length of the HC and LC buffers as a function of the HC rate ratio α with/without misalignment (dotted/solid) for our proposed MC-SC scheme and a time sharing scheme as baseline.

approach, where a portion of each time slot is allocated to transmit HC data with enhanced reliability over both transmission paths, while the remaining time is used to transmit LC data through the direct link. When $\alpha = 0$, the average (LC) queuing delay is approximately 2.5 time slots. Due to the different reliability levels of HC and LC data, the HC delay achieved for sufficiently small α is much lower, approximately by a factor of 10. With time sharing, the LC delay increases as soon as some data is classified as HC ($\alpha > 0$), whereas the HC delay grows more slowly. The system becomes unstable around $\alpha > 0.18$. In contrast, our proposed scheme allows for a significantly larger portion of data to be transmitted as HC with short delays. In fact, the average queuing delay even exhibits a slight decrease, reaching a minimum at $\alpha = 0.39$. This is a result of the gain in sum-throughput that can be achieved with superposition coding. The overall delays remain low when less than 50% of the packets are treated as HC data, and the system becomes unstable at $\alpha > 0.63$.

Fig. 10 shows the normalized peak queue length, defined as $\max_t \frac{Q_h(t)}{\alpha A}$ and $\max_t \frac{Q_l(t)}{(1-\alpha)A}$ for the HC and LC buffer, respectively. Again, we compare the MC-SC scheme with the time-sharing approach across varying α . Furthermore, the performance is evaluated with and without beam misalignment. Due to the higher outage probability associated with LC transmission, packets may accumulate in the LC buffer until successful delivery to the UE. As a result, the peak queue length of HC data remains significantly lower than that of the LC queue. The peak queue length follows a trend similar to the average delay, showing that with MC-SC, queues remain stable without considerable packet accumulation over a much larger range of α . Under beam misalignment, both schemes experience increased buffer congestion, and the range of α , for which queues are stabilized, is reduced. However, with MC-SC, the peak queue length stays stable for a broad range of α (up to 0.4) even in the presence of misalignment. Compared to time sharing, MC-SC increases the maximum α that

ensures stabilized queues by approximately 2.6 times in the absence of misalignment, and even by a factor of four under misalignment conditions. Furthermore, while LC queue length slightly increases under misalignment in that range, the HC queue peak is barely affected by pointing errors until α reaches approx. 0.55, indicating its robustness against misalignment. Across the stable α range, the HC queue peak is around three times lower than the LC peak under perfect beam alignment, and about four times lower when pointing errors occur.

As a result, the simulations demonstrate the effectiveness of our proposed criticality-aware scheme in achieving low delays for particularly critical data, while maintaining queue stability. Furthermore, with MC-SC, the portion of critical data can be substantially enhanced compared to a time sharing approach, without causing packet accumulation.

V. CONCLUSION

This paper addresses key challenges in THz communication: the severe path loss and high sensitivity to blockage and beam misalignment, which lead to link intermittency and a fundamental rate-reliability tradeoff. To overcome these issues, we introduce a novel criticality-aware transmission framework that effectively balances reliability and throughput in a resource-efficient manner. The proposed approach employs a mixed-criticality superposition coding scheme for downlink transmission, leveraging the diversity provided by a highly intermittent LoS link and a more stable RIS-assisted path. The scheme prioritizes highly critical data to ensure reliability under adverse conditions, while low-criticality data is transmitted opportunistically when the LoS path is available. By modeling a data queuing system at the base station, we formulated a power allocation problem to ensure queue stability and solve it using an iterative SCA-based algorithm. Key findings from our simulation results include:

- (1) The proposed framework ensures robust transmission of HC data even under severe blockages, leveraging RIS-enabled path diversity.
- (2) Opportunistic use of the LoS link under favorable conditions enables substantial throughput gains without compromising reliability.
- (3) The framework adapts to increased blockages and misalignment by relying more on the RIS link, demonstrating robustness in challenging conditions.
- (4) Misalignment mitigation techniques, such as beamwidth adjustment, are critical to fully exploit the RIS benefits, ensuring stable connectivity for both HC and LC data.

Compared to time-sharing or single-stream methods, our SC approach achieves higher critical data rates and superior total throughput without causing packet accumulation or increased queuing delays. Thereby, it substantially narrows the throughput gap with idealized benchmarks like beam switching. It provides a robust and resource-efficient framework for deploying RIS in THz systems, that addresses the

interplay among blockage, misalignment, and RIS functionalities. These insights are vital for achieving both reliability and high throughput in next-generation wireless networks.

APPENDIX

The non-convex power allocation problem can be solved using a SCA approach. We derive a convex approximation of (32) as follows:

First, we introduce auxiliary variables $\gamma = [\gamma_h, \gamma_l]$. Hence, we can rewrite problem (32) as follows:

$$\max_{\delta, \mathbf{p}, \mathbf{R}, \gamma} \min\{\delta_h, \delta_l\} \quad (34)$$

$$\text{s.t.} \quad (32a), (32b), (32c), (32f), \quad (34a)$$

$$R_h \leq B \log_2(1 + \gamma_h), \quad (34b)$$

$$R_l \leq B \log_2(1 + \gamma_l), \quad (34c)$$

$$\gamma_h \leq \Gamma_h(\beta, \epsilon_{th}), \quad \beta \in \{(0, 1), (1, 0), (1, 1)\}, \quad (34d)$$

$$\gamma_l \leq \Gamma_l(\beta, \epsilon_{th}), \quad \beta_d = 1. \quad (34e)$$

Next, we adopt the quadratic transform proposed in [47] to handle the fractional SINR expressions. By introducing the auxiliary variables $\mu = [\mu_{h,(0,1)}, \mu_{h,(1,0)}, \mu_{h,(1,1)}]$ and applying the approach from [47], we obtain the functions

$$\begin{aligned} g_{h,\beta}(\mathbf{p}, \gamma) &= \gamma_h - 2\mu_{h,\beta} \sqrt{\beta_d \eta_d^2 \rho_d(\epsilon_{th}) p_h^{(d)} + \beta_r \eta_r^2 \rho_r(\epsilon_{th}) p_h^{(r)}} \\ &\quad + \mu_{h,\beta}^2 \left(\beta_d \eta_d^2 \rho_d(\epsilon_{th}) p_l^{(d)} + \beta_r \eta_r^2 \rho_r(\epsilon_{th}) p_l^{(r)} + \sigma_n^2 \right), \end{aligned} \quad (35)$$

$$g_l(\mathbf{p}, \gamma) = \gamma_l - \frac{1}{\sigma_n^2} \eta_d^2 \rho_d(\epsilon_{th}) p_l^{(d)}. \quad (36)$$

The optimal μ for fixed \mathbf{p} and γ can be obtained by setting the derivative of (35) to zero. Thus, we have

$$\mu_{h,\beta}^* = \frac{\sqrt{\beta_d \eta_d^2 \rho_d(\epsilon_{th}) p_h^{(d)} + \beta_r \eta_r^2 \rho_r(\epsilon_{th}) p_h^{(r)}}}{\beta_d \eta_d^2 \rho_d(\epsilon_{th}) p_l^{(d)} + \beta_r \eta_r^2 \rho_r(\epsilon_{th}) p_l^{(r)} + \sigma_n^2}. \quad (37)$$

As for constant μ , the functions (35) and (36) are convex in \mathbf{p} and γ , the optimization problem (34) can be approximated by a convex problem with fixed μ :

$$\max_{\delta, \mathbf{p}, \mathbf{R}, \gamma} \min\{\delta_h, \delta_l\} \quad (38)$$

$$\text{s.t.} \quad (32a), (32b), (32c), (32f), (34b), (34c), (38a)$$

$$g_{h,\beta}(\mathbf{p}, \gamma) \leq 0, \quad \beta \in \{(0, 1), (1, 0), (1, 1)\}, \quad (38b)$$

$$g_l(\mathbf{p}, \gamma) \leq 0. \quad (38c)$$

Thus, the optimal power allocation is obtained via an iterative SCA-based algorithm. That is, the approximated problem (38) is solved using a convex optimization solver such as CVX [48], and the auxiliary variables μ are alternately updated following (37). The procedure is summarized

Algorithm 1 Power Allocation for the MC-SC Scheme

Input: transmission parameters $P_{\max}, B, \bar{A}, \alpha$, channel parameters $\eta_d, \eta_r, q_d, q_r, \sigma_{m,d}^2, \sigma_{m,r}^2, N_0$, beam parameters w_d, w_r, a_U, a_{RIS} , design parameters ϵ_{th}, w_h, w_l

Output: $\mathbf{p}^*, \mathbf{R}^*$

- 1: Calculate $\rho_d(\epsilon_{th}), \rho_r(\epsilon_{th})$ based on (6), (14)
- 2: Calculate misalignment probabilities $q_{m,d}, q_{m,r}$ based on (8), (10), (12), and (28)
- 3: Calculate outage probabilities $P_{out,h}, P_{out,l}$ based on (29), (30)
- 4: Initialize \mathbf{p}
- 5: **repeat**
- 6: $\mu \leftarrow$ compute (37)
- 7: $\mathbf{p}, \mathbf{R} \leftarrow$ solve (38) for fixed μ using convex optimization solver
- 8: **until** Convergence
- 9: $\mathbf{p}^* \leftarrow \mathbf{p}, \mathbf{R}^* \leftarrow \mathbf{R}$

in Algorithm 1. Note that with the quadratic transform approach from [47], the iterative optimization algorithm is guaranteed to converge to a stationary point of the original problem (32).

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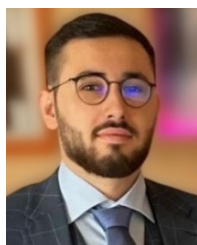
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